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Evaluation of social life-cycle performance of buildings: theoretical framework and impact assessment approach

Siyu Liu[1], Shunzhi Qian[1,*]

1. School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

* Corresponding author (szqian@ntu.edu.sg)

Abstract

Recognizing the importance of building-specific social impact assessment tools to the achievement of social sustainability of building projects, this study developed a methodological framework for social life cycle assessment of buildings through stakeholder-based approach, which includes the following four parts. (1) An assessment framework was proposed considering four stakeholders, including worker, occupant, local community and society, and impact subcategories associated with different social concerns; (2) Indicators were selected for each subcategory based on the assessment objective and data availability. They were categorized into three groups, including quantitative indicators in generic analysis, as well as quantitative and semi-quantitative indicators in site-specific analysis, and corresponding scoring method were provided; (3) Weights among impact subcategories were generated through questionnaire survey based on analytic hierarchy process method, and weights among life-cycle phases were determined considering the possibility to place control as well as level of concern of construction practitioners; (4) The proposed method was applied to a case study comparing two buildings with different construction methods, namely prefabricated prefinished volumetric construction (PPVC) project and semi-fabrication project. The result suggests that PPVC project outperforms semi-fabrication one in terms of life-cycle social performance. This is mainly caused by its capability to protect worker's health and safety as well as its contribution to technology development.

Keywords

Social sustainability assessment; social life cycle assessment; multi-stakeholder approach; Prefabricated prefinished volumetric construction; modular construction; semi-prefabricated construction

Nomenclature

AC	Activity Contribution
AFR	Accident Frequency Rate
AHP	Analytic Hierarchy Process
CFPR	Consistent Fuzzy Preference Relation
CPS	Country-Level Performance Score
E-LCA	Environmental Life Cycle Assessment
GHG	Greenhouse Gas
ILO	The International Labour Organization
ISO	The International Organization for Standardization
MOM	The Ministry of Manpower (Singapore)
O&M	Operations & Maintenance
PDCA Cycle	Plan-Do-Check-Act Cycle
PPVC	Prefabricated Prefinished Volumetric Construction
PRS	Performance Reference Scale
PRV	Performance Reference Value
QP	Quantity Proportion
SETAC	Society of Environmental Toxicology and Chemistry
S-LCA	Social Life Cycle Assessment
SPS	Social Performance Score
UNEP	The United Nations Environment Programme
UNICEF	The United Nations International Children's Emergency Fund
USGS	United States Geological Survey
WHO	The World Health Organization

1. Introduction

Buildings and their relevant processes have significant influence on three key dimensions of sustainability, i.e., environmental, economic and social dimensions, in both positive and negative manners (Kamali and Hewage, 2017). On one hand, buildings satisfy human being's basic needs and improve life quality, create numerous employment opportunities, and further contribute greatly to national economy (Love and Irani, 2004; Zuo and Zhao, 2014). On the other hand, building projects consume raw materials and energy to construct and operate, release greenhouse gases (GHG), generate solid waste, cause pollution and occupy land (Ding, 2008; Ma and Cai, 2019; Ma et al., 2018; Ma et al., 2017; Wong and Fan, 2013). In addition, building projects are responsible for some safety and health issues due to high possibility of unsafe working environment during construction process (Shen et al., 2010; Zhang et al., 2015). The quality of building products and indoor environment also have great effect on occupational health (Zuo et al., 2017).

With increasing awareness of above-mentioned issues, efforts have been made in the construction industry to address them in the last decades, shifting from traditional focuses of time and cost only, towards much broader ones. However, these efforts are mainly directed at reducing negative environmental impacts while social sustainability has not been properly addressed (Gould et al., 2017; Hutchins and Sutherland, 2008). Social sustainability by nature involves multi-faceted social values, which are sequentially influenced by plentiful stakeholders (Almahmoud and Doloi, 2015). In particular, a socially sustainable building project is supposed to respond to the different requirements of multiple stakeholders involved in the whole process of the building project development, including not only the final users but also construction personnel, suppliers and local communities (Hussin et al., 2013; Valdes-Vasquez and Klotz, 2012; Wong and Fan, 2013).

However, social impact assessments with a proper coverage of relevant stakeholders for building evaluation is still lacking , as highlighted in previous studies (Valdes-Vasquez and

Klotz, 2012; Zhao et al., 2012). This study thus aims to develop a methodological framework for social sustainability assessment of buildings through stakeholder interest-based approach. In this work, social life cycle assessment (S-LCA) method was adopted as the basis to assess the potential positive and negative social impact of products, processes, services or systems throughout their life cycle. Such life-cycle perspective enables the consideration of potential transfer of impacts between different life cycle phases, impact categories and regions.

S-LCA is often regarded as a parallel to the environmental life cycle assessment (E-LCA) (Ekener et al., 2018). However, unlike E-LCA that is standardized by ISO 14040 and 14044, there is no consensus on the specific or consistent S-LCA method. One significant step towards its standardization is the publication of *Guidelines for Social Life Cycle Assessment of Products* by UNEP/SETAC Life Cycle Initiative (2009) (hereafter referred to as *the Guideline*), which provides a general framework with methodological sheets for 31 social impact subcategories regarding different aspects of social concerns. In *the Guideline*, social impacts are observed in five stakeholder categories, including workers, local community, consumer, society and value chain actors. Such stakeholder-based approach is consistent with our initial consideration for framework development.

The Guideline has been applied and tested in many case studies in various industrial contexts with different objectives, including some building-specific analyses, such as (Dong and Ng, 2015; Hosseinijou et al., 2014). Franze and Ciroth (2011) developed a checklist method to compare the social impacts of rose production and cutting and packaging process in Ecuador and Netherlands considering 19 impact categories associated with five stakeholders. Traverso et al. (2012) compared social impacts of the production of three photovoltaic modules considering six impact categories related to workers. Foolmaun and Ramjeeawon (2013) proposed a scoring method for quantitative social impact assessment and conducted a comparative S-LCA study of four disposal scenarios of used polyethylene terephthalate bottles. Hosseinijou et al. (2014) performed a comparative assessment of life cycle social impacts of concrete and steel as building materials with the combination of material flow analysis. Some other studies aims to identify social hotspots of different products, such as laptop computers (Ciroth and Franze, 2011; Ekener-Petersen and Finnveden, 2013), palm oil biodiesel (Manik et al., 2013) and fertilizers (Martínez-Blanco et al., 2014).

While using *the Guideline* as the basis for their analysis, previous cases studies vary greatly regarding the detailed methodological choices to conduct S-LCA studies depending upon difference purposes and application scenarios. This means *the Guideline* at this stage is still adopted as a methodological skeleton rather than a technical handbook (Macombe et al., 2011; Reitinger et al., 2011). Several key knowledge gaps regarding methodological choices are identified from previous studies. The fundamental one is the identification of relevant stakeholders and social issues. Although *the Guideline* identifies hundreds of social issues, not all of them are directly relevant to the analysis. Social issues can be identified differently under different regional and industrial scenario, and can be changed over time. Therefore, a set of social issues associated with various stakeholders related to different life cycle phases of buildings needs to be understood before conducting S-LCA. Sequentially, weights among the selected impact categories need to be determined properly instead of being assumed to be equally significant.

Another knowledge gap is associated with the social indicators to characterize the social issues identified. In S-LCA studies, data can be collected from either generic or site-specific sources, and the impacts can be captured through quantitative, semi-quantitative or qualitative indicators. Both data source and indicator type, and even different policy or industrial requirement, may lead to different choices of indicator for a certain impact category. Hence, a specific set of indictors needs to be developed depending on the goal and scope definition as well as data accessibility. Besides, the choice of the reference performance for each indicator needs to be justified for quantitatively illustrating social performance. The reference performance could be determined based on the minimal legal requirements, sectorial standards and average performance, as well as the best expected practices within the industry (Revéret et al., 2015).

This study contributes to the current body of knowledge on building-specific social sustainability assessment by proposing a building-specific S-LCA method through addressing the above-mentioned knowledge gaps existing in general S-LCA method. This study proposes a set of impact categories and assessment criteria that could be suitable and applicable for building-specific social impact analysis. Based on such assessment framework, social life-cycle performance of a building can be measured and aggregated in a sustainable building evaluation scheme or a decision-support tool. In addition, this study provides a possible approach that can integrate both generic and site-specific information into a quantitative evaluation, which could also be applied in S-LCA studies in other industrial contexts outside the construction industry.

In the following sections, the proposed theoretical framework for social sustainability assessment is presented in Section 2, with the definition of stakeholder and relevant impact subcategories. The methodology for social impact assessment is elaborated in section 3, including indicators selection, weights determination, and calculation of social impact scores. This is followed by a case study comparing two building structures with different construction methods. Conclusion and future work are discussed in the last section.

2. Theoretical framework for social sustainability assessment

This section presents the selection and definition of social impact categories, which form the theoretical framework for social sustainability assessment of buildings. Consistent with the stakeholder-based approach in *the Guideline*, stakeholder categories were firstly identified to cover groups of people that are potentially affected by life-cycle activities, followed by the selection of social subcategories under each stakeholder category to illustrate different aspects of social concerns.

2.1. Selection and definition of stakeholder categories

In this proposed assessment framework, four main life cycle phases of buildings were considered, including raw material extraction, building material or products manufacturing, on-site construction, and operation and maintenance (O&M). Demolition and reuse-recycle stages are not included in this study mainly due to the limited responsibility of building project team. S-LCA is an organization-based assessment, which is not a process-based assessment as environmental LCA) (Dreyer et al., 2010). As for a building project, several companies representing owners, contractors, designers, etc. are involved and form a temporary and dynamic project team, which is the organization in building-specific S-LCA. This project team has direct control on construction and operation phases and has indirect control on production and raw material extraction through decisions on building designs and purchasing plans. When the building reaches to its end-of-life stage (which could be 50 years later), demolition and disposal will not be completed by the same project team, and activities in these phases are out of the control of this project team. Therefore, system boundary in this assessment framework was set as “cradle to service”.

Accordingly, four stakeholder categories were identified, including: 1) workers, which refer to people working in manufacturing plant or on mining/construction site; 2) occupants of the building; 3) local communities, which refer to those who live in the close proximity to a production site or construction site, and thus directly affected by the production or construction activities; and 4) society, which refers to the general public in the region where the building project is located and is indirectly affected regarding acknowledged social values (Manik et al., 2013; Siebert et al., 2016). Other value chain actors were excluded since their identification is quite ambiguous and data collection from them are quite difficult, if not impossible, in the building supply chain (Dong and Ng, 2015).

Fig.1 illustrates how activities within different life cycle phases are linked to the stakeholder categories. For raw material extraction and manufacturing phase, a number of materials or products are required, and thus various organizations are involved and cause different impacts due to different regional context and organizational conduct. Consequently, assessment should be performed separately by organizations. As for the construction and O&M phase, the integrated organization, i.e., project team, will be assessed. Stakeholder category "society" is not directly linked to any life cycle phase; it is how the development of a certain building project causes the change of industrial environment or society (specifically Singapore in this study) that will be examined.

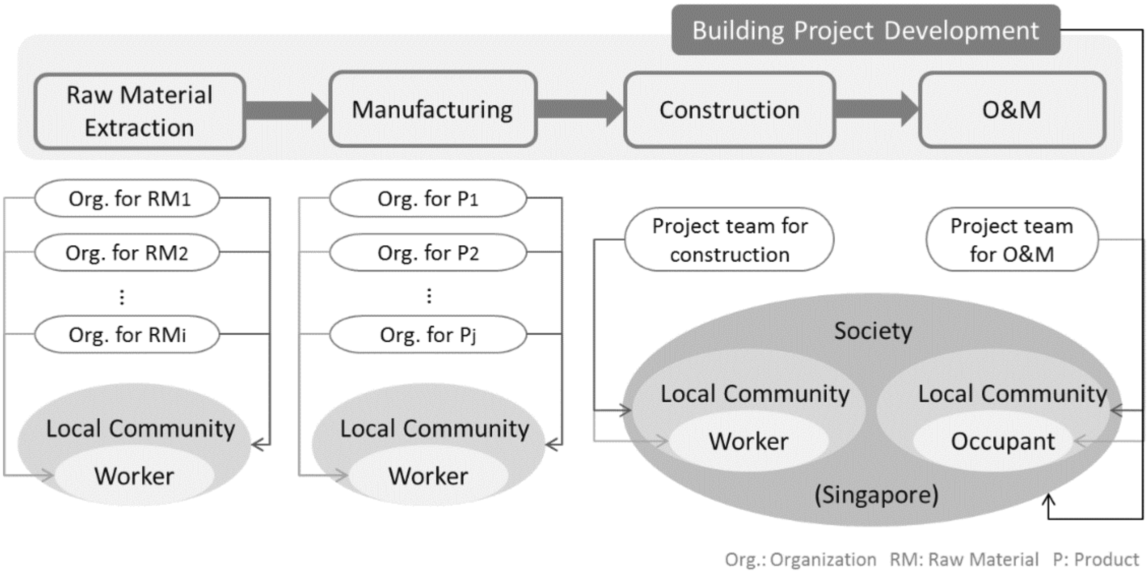


Fig.1 Relationship between life cycle phases and stakeholder categories

2.2. Selection of social impact subcategories

The selection of social impact subcategories was based on *the Guideline* and 15 previous studies that developed building-specific criteria for social impact assessment (Ali and Al Nsairat, 2009; Almahmoud and Doloi, 2015; Alwaer and Clements-Croome, 2010; Andrade and Bragança, 2011; Bragança et al., 2010; Chan and Lee, 2008; Chen et al., 2010; Dave, 2011; Kamali and Hewage, 2015; Nguyen and Altan, 2011; Pan et al., 2012; Shen et al., 2010; Shen et al., 2007; Valdes-Vasquez and Klotz, 2012; Yunus and Yang, 2011). It is worth mentioning that previous building-specific studies usually only focus on construction and O&M phases, while enlarged boundary in this study, i.e., including four main life-cycle phases, leads to a broader set of impact categories.

Two-phase selection was conducted. The initial selection was based on *the Guideline* and previous S-LCA case studies that adopted *the Guideline*'s framework disregarding their case scenarios (Chen and Holden, 2017; Wang et al., 2016). Subcategories irrelevant to our study were excluded, such as delocalization and migration issues, and prevention of armed conflicts and corruption. Secondly, building-specific criteria (which refers to subcategories in the context of S-LCA) for social impact assessment proposed in the 15 studies were reviewed to refine the selection, which were then classified into stakeholder categories. Social impact categories included in this study are summarized in Table 1. Detailed explanations of these subcategories are provided in Supplementary Material.

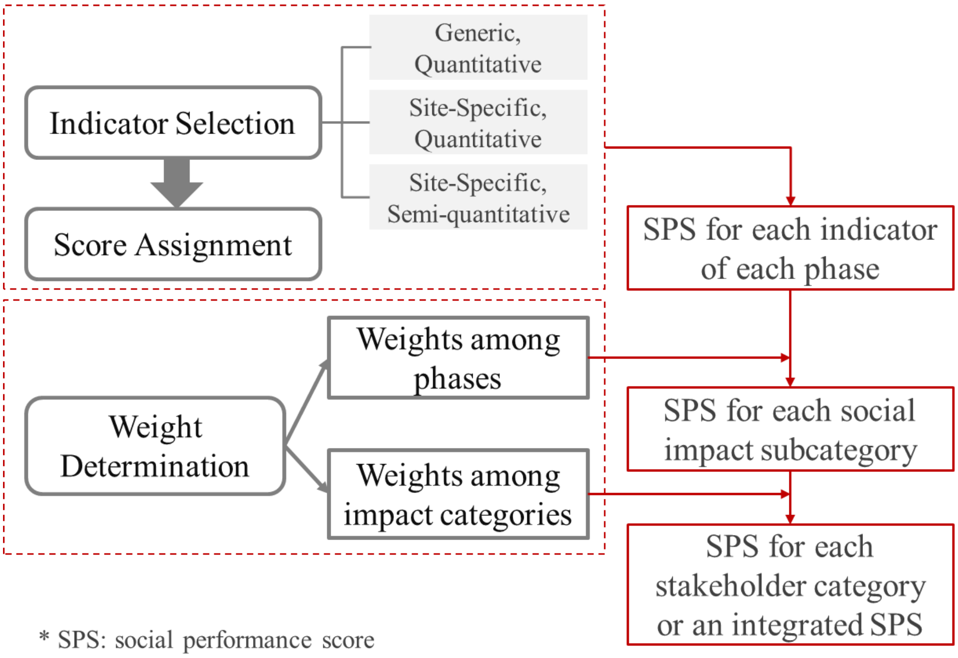
Table 1 Selection of stakeholder categories and subcategories

Social Impact Category		Source	
Stakeholder Category	Subcategory	*the Guideline* (original expression if any change)	Papers (count of papers mentioning a certain subcategory)
Worker	Health and safety of workers	√	√ (8)
	Fair Salary	√	×
	Working Hours	√	×
	Discrimination	√	×
	Forced Labour	√	×
	Child Labour	√	×
Occupant	Functionality and Usability	√ (safety & health)	√ (8)
	Health and Comfort	√ (safety & health)	√ (14)
	Accessibility	×	√ (6)
	Feedback Mechanism	√	×
Local Community	Safety and Health	√(safe, healthy and secure living conditions)	√ (9)
	Accessibility	√ (access to material resources)	√ (6)
	Integration and Interaction	√ (local engagement; cultural heritage)	√ (7)

	Local Employment	√	√ (6)
Society	Technology development	√	√ (3)
	Public commitments to sustainability issues	√	×

3. Methodology for social impact assessment

This section addresses the issues related to social impact assessment, which are illustrated by Fig.2. One or more social indicators were selected to characterize each impact subcategory (as listed in Table 1), and the justification for indicator selection is provided in section 3.1. Three groups of indicators were used in this methodology and they applied different scoring methods, which are explained separately in section 3.2. To integrate these social performance scores (SPS), weights among life-cycle phases and impact categories were generated, which are presented in section 3.3. Accordingly, SPS for each social impact subcategory can be obtained by integrating SPS for each indicator of each phase and phase weights. Furthermore, an integrated SPS or SPS for each stakeholder category can be obtained using subcategory weights.



* SPS: social performance score

Fig. 2 methodological framework for social impact assessment

3.1. Indicators selection

Indicator selection is influenced by the nature of the assessment objective and data availability. As discussed in previous S-LCA studies (Dreyer et al., 2006; Jørgensen et al., 2008; Kruse et al., 2009), site-specific data obtained by investigating organizational operation are more favourable to evaluate social impact compared with generic statistical data. However, such information is not always available. From life cycle perspective, main activities of a project team lie in construction and O&M phases, and the building evaluation is always conducted during the design phase, or before buildings being put into operation. The availability of detailed information will be lower if the activities are located farther from the center, as indicated in Fig.3. It is impossible to trace back where a certain raw material was extracted exactly, not to mention to know which specific company it is from. As for manufacturing phase, more specific information may be obtained from first tier supplier of building material or components, however, most of information regarding organizational-level management are still lacking or out of the control of those who conduct social assessment. Therefore, considering data availability, this study uses both generic and site-specific data, as shown in Fig. 3, which influences the indicator selection.

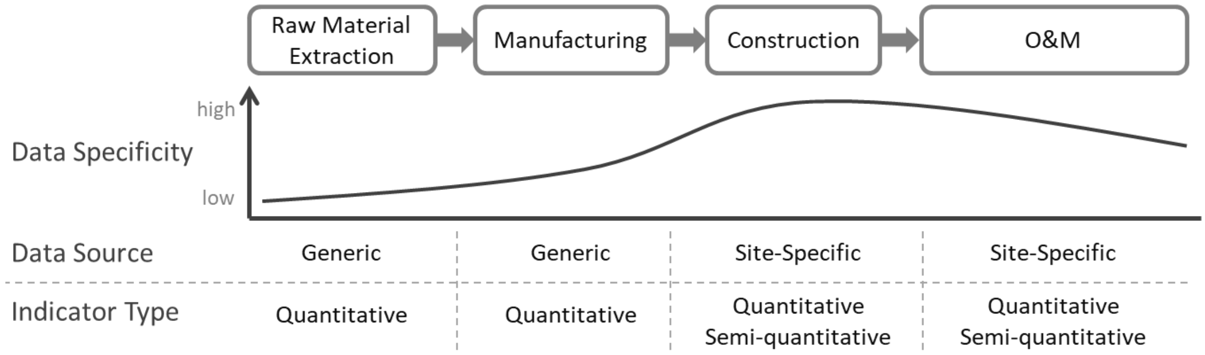


Fig.3 Data specificity change along life cycle phases and their corresponding data sources and indicator types

To obtained quantitative results, indicators can be quantitative or semi-quantitative. Quantitative indicators describe assessed issues using specific values, for instance, number of work accidents. Semi-quantitative indicators are quantification of qualitative indicators which usually use a scoring system or a yes/no form, for example, giving score for company performance regarding human rights protection using a scale of 1 to 5. As shown in Fig. 3, for the analyses based on the generic data, indicators are all quantitative since statistical data at the country and industry level are used. As for site-specific analyses, both quantitative and semi-quantitative indicators are involved, since quantitative indicators sometimes cannot properly describe the real case situation (Dreyer et al., 2010).

Based on the previous discussion, indicators were selected separately for generic analysis and site-specific analysis involving both quantitative and semi-quantitative indicators. The selection of indicators and their corresponding data sources, as summarized in Table 2, were on the basic of methodological sheets of *the Guideline* (Benoît et al., 2009); further selection was based on the relevancy to construction sector context or Singapore context and data availability.

Table 2 Selection of indicators for generic analysis and site-specific analysis

Subcategory	Generic Analysis		Site-Specific Analysis	
	Indicators	Sources	Indicators	Sources
Health and safety (worker)	Non-fatal and fatal occupational injuries per 100,000 workers	(Hämäläinen et al., 2006)	○ Status of managerial practices ● Accident frequency rate	On-site observation Workers' feedback Human resources and management records Project management records …
Fair Salary	Ratio between average sector wage and living wage	(Communities, 2009; ILO, 2017)	○ Status of managerial practices ● Percentage of workers whose wages meet at least legal minimum wage or sectorial standard. ● Percentage of workers who are paid a living wage.	
Working Hours	Excessive weekly working hours per employed person compared with 48 hours	(ILO, 2017)	○ Status of managerial practices ● Contractual working hours ○ Management of overtime	
Discrimination	Gender inequality index	(Selim Jahan et al., 2016)	○ Status of managerial practices ● Numbers of incidents of discrimination	
Forced Labour	Proportion of population in modern slavery	(WalkFree, 2016)	○ Status of managerial practices ● Numbers of forced labor	
Child Labour	Percentage of children 5-14 years old involved in child labour	(UNICEF, 2017)	○ Status of managerial practices ● Numbers of child labor	
Functionality and Usability	-		○ Status of design consideration ○ Performance regarding meeting functionality needs and provision of essential amenities and building equipment	On-site observation and audit Design document and parameters Occupants' feedback managerial records …
Health and Comfort	-		○ Status of design consideration ○ Performance regarding indoor air quality, acoustic comfort, hydrothermal comfort and visual comfort	
Accessibility (occupants)	-		○ Status of design consideration ○ Performance regarding proximity to public transportations and amenities	
Feedback	-		○ Status of managerial practices	

Mechanism			○ Performance regarding efficiency of dealing with fault reporting and general enquiries	
Safety and Health (Local community)	Reliability of police services Burden of disease Dealing with construction permits	(Klaus Schwab et al., 2018) (WHO, 2015) (WorldBank, 2017)	○ Status of managerial practices ○ Performance regarding controlling disturbance to surroundings regarding dust emission, noise emission, and preventing safety issues	On-site observation Feedback of neighbourhoods and pedestrian project records …
Accessibility (Local community)	Percentage of population with access to improved water source and improved sanitation facilities Quality of road	(WorldBank, 2016) (Klaus Schwab et al., 2018)	○ Status of managerial practices ○ Performance regarding preventing mobility disturbance (construction phase) ○ Status of design consideration ○ Performance regarding proving open places, paths and facility for public (O&M phase)	
Integration and Interaction	Transparency of government Policymaking Public trust in politicians	(Klaus Schwab et al., 2018)	○ Status of managerial practices ○ Performance regarding the preservation of local characteristics, and involvement of neighbourhoods into project-related activities, such as design and construction process planning, knowledge sharing and skill transfer	
Local Employment	Unemployment rate Local supplier quantity	(WorldBank, 2016) (Klaus Schwab et al., 2018)	○ Status of managerial practices • Percentage of workforce hired locally • Percentage of spending on locally-based suppliers.	
Technology development	-		○ Status of managerial practices ○ Performance regarding technology development strategies	Organization and project report …
Public Commitment to Sustainability Issues	-		○ Status of managerial practices ○ Performance regarding public sustainability reporting	

• Quantitative indicator using site-specific data
○ Semi-Quantitative indicator using site-specific data

3.2. Scoring of indicators

As listed in Table 2, three groups of indictors are involved, including quantitative indicators in generic analysis, as well as quantitative and semi-quantitative indicators in site-specific analysis. Indicators need to be scored and normalized to a range of -2 to +2 in order to be further integrated to single social performance scores. With different forms and actual meanings, these indicators vary greatly on scoring and normalization process, which will be explained in the following parts.

3.2.1. Quantitative Indicators in Generic Analysis

Before conducting generic analysis, country-level performance scores (CPS) regarding each impact indicator need to be prepared using national statistical data. Statistical data were collected from several online databases or international reports, as indicated in Table 2, and were normalized to a range of -2 to +2. Typically, positive values represent above-average or favourable social performance, while negative ones show poor social performance or negative impact. For example, country-level statistics regarding non-fatal occupational injuries rate (Hämäläinen et al., 2006) were normalized between -2 to +2 where country with lowest injuries rate was assigned a score of 2, and country with the highest injuries rate was assigned a score of -2. As mentioned, the normalization rule is based on the actual social meaning of the indicator, rather than all being normalized according to maximum and minimum values. For example, most of the countries do not have issues of child labor according to statics (UNICEF, 2017); thus countries with 0% were scored as 2, while others are normalized to -2~0.

With country-level performance scores, data collection for generic analysis focuses on the identification of main countries involved in certain phases (particularly raw material extraction and production phase), and the activity contribution of these countries. In this study, weight proportions of building materials serve as the basis for calculation, as adopted in previous studies (Ekener-Petersen and Finnveden, 2013; Gould et al., 2017); while activity contributions of countries are connected to these materials through worldwide extraction statistics and export or import data.

For raw material extraction phase, weights of raw materials are estimated based on the quantity of building materials that can be identified using Bill of Quantity or other project records. These materials can be split into raw materials based on general production information of a certain material. For example, integrated steelmaking route requires 1.4 kg of iron ore, 0.8 kg of coal, 0.3 kg of limestone and 0.12 kg of recycled steel to produce 1 kg of crude steel (Worldsteel, 2018). Such information indicates the extraction forms of raw materials and allows the conversion to percentage composition of all the raw materials involved. For each raw material, main extraction locations and percentage of extraction from each country can be obtained from the statistics. In this study, Mineral Commodity Statistics (USGS, 2017) and World Mineral Production (Brown et al., 2014) were used to identify dominant countries that contribute around 90% of total world extraction, which are then used to represent all contributing countries for simplification.

For manufacturing phase, indicators are scored following the similar process. Differently, the activity contribution of each country could be calculated based on more specific and accurate information, such as project purchasing or supplier records, showing actual origins of a certain building material or product. Alternatively, for building materials or products that are directly related to assembly or construction activities in Singapore, country activity distribution can be determined using Singapore-specific statistical data, such as import statistics (COMTRADE, 2017; Simoes, 2017), instead of using worldwide statistical data. For example, considering sand usage in Singapore relies greatly on import, country activity contribution for sand was estimated using import data, according to which Malaysia (65.3%), Vietnam (20.4%) and Cambodia (14.3%) are the top three contributors for sand mining.

Accordingly, the contribution of activities in jth country (activity contribution, AC_j) involved in a certain life cycle stage can be obtained through integrating quantity proportion of kth material (quantity proportion, QP_k) and country activity contributions regarding individual materials (AC_{jk}), as indicated by Equation (1).

$$AC_j = \sum QP_k \times AC_{jk} \tag{1}$$

With the normalized social performance score of jth country for ith indicator (country-level performance score, CPS_{ij}), and the activities contribution occurred in each country (AC_j), the integrated normalized social performance score of ith indicator (social performance score, SPS_i) can be obtained by,

$$SPS_i = \sum CPS_{ij} \times AC_j \tag{2}$$

3.2.2. Site-specific Analysis

Site-specific analysis focuses on the analysis on the project-specific social performance regarding each impact subcategories, as well as organizational efforts in management practices to improve or prevent certain social issues. There are some previous studies (Dreyer et al., 2010; Wang et al., 2016) that developed site-specific assessment methods or models; however, these studies only focus on organizational operations to indirectly identify the risk of violation incidents, while direct social performances regarding certain impact subcategories were not investigated. In this study, site-specific analysis covers both organizational managerial practices and direct social performance.

(1) Evaluation of organizational performance

For organizational performance, Deming Cycle, also known as PDCA Cycle, was used as a reference to develop evaluation framework. Four aspects relevant to plan (P), do (D), check (C) and act (A) are to be investigated. Please note that in below discussion an organization refers to a building project team, instead of a single company.

For *plan* aspect, it evaluates whether an organization plans or designs properly based on legislation and sustainability principles, establishes organizational sustainability policy, and clearly communicates to relevant managers and employees. For *do* aspect, it evaluates whether organizational practices are complied with legislation and whether there is any sustainable practice to prevent violation or achieve improvement. *Check* aspect is about whether an organization monitor, audit or benchmark social related performance and/or establish a system to receive complaints/feedbacks, and whether it records properly. *Act* aspect is closely related to the *Check* results. On one hand, it evaluates whether organization responses properly if there is any violation incidents or complaints/feedbacks; on the other hand, it evaluates whether organization reviews problems existed in practice and determines whether any changes or revisions are needed in strategy and practices.

Scores for organizational performance, using semi-quantitative indicators, are obtained based on experts' verbal and qualitative assessments and their further conversion to numbers. The assessment is based on the performance reference scales (PRS), including five performance levels, namely, very poor (VP), poor (P), fair (F), good (G), very good (VG), and corresponding performance descriptions of each level. An example of the performance reference scale is provided in Supplementary Material. Management team members, such as engineers and project managers, are required to carefully check the descriptions provided and select the suitable performance level based on their opinion.

Assessment results are then converted into triangular fuzzy numbers $\tilde{x}_i^m = (a, b, c)$ using Fig. 4 to represent mth evaluator's assessment regarding ith indicator, where a, b, and c are the membership function parameters. Adoption of fuzzy numbers can address the imprecision and uncertainty that is inherent to the human judgments in the decision-making process (Ren et al., 2015). Later, all the assessment results are aggregated into group evaluation results by applying the fuzzy averaging operator, which is defined by:

$$\tilde{x}_{ik} = \frac{1}{\mathrm{M}}[\tilde{x}_i^1(+)\tilde{x}_i^2(+)\ldots(+)\tilde{x}_i^M], \tag{3}$$

where M is the number of experts.

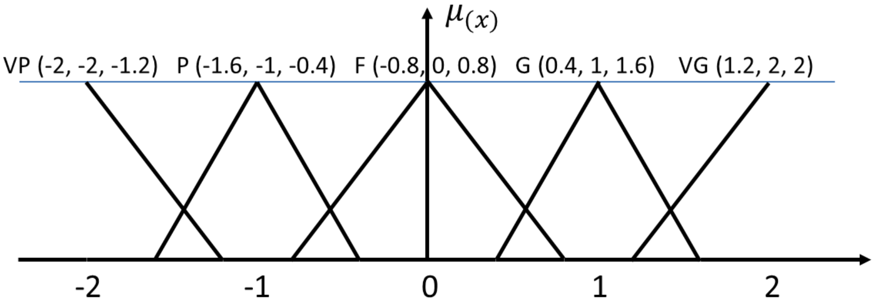


Fig. 4 Membership function of linguistic terms

Note: Linguitic scales and their corresponding fuzzy numbers adopt the definition of (Hsieh et al., 2004) which is propotionally transformed between -2 and 2.

Finally, fuzzy evaluation results are then defuzzified based on centroid of area method, as indicated by Eq. (4), which are the scores for semi-quantitative indicators.

$$x_i' = \frac{\mathrm{a+b+c}}{3} \tag{4}$$

(2) Evlauation of direct social performance

Indicators of direct social performance could be both quantitative and semi-quantitative, as indicated in Table 2. For semi-quantitative indicators, scoring process is similar to the process to evaluate organizational performance, which is also obtained from evaluators' verbal and qualitative assessments based on PRS and their further conversion to numbers using fuzzy numbers. Differently, evaluators should be multi-stakeholder, which may include occupants, local community, workers, and so on, depending on their relevancy.

Scores for quantitative indicators are obtained using performance reference values (PRVs), which can be country and/or sector average performance values. Specific calculation depends highly on the actual meaning of the indicators. For instance, to score performance regarding local employment, percentage of local workforce in a project is selected as indicator, and both sector and country statistical data were used as PRVs, being 14% and 63% respectively. 63%, rather than 100%, is given the score of +2, considering 63% is seen as the optimistic (best) performance in the context of Singapore; 14% is given the score of 0, indicating the standard and average performance level. Accordingly, performance score is obtained through normalizing project-specific percentage of local workforce, e.g. project with 20% being local workforce obtains the score of 0.24 ($= (20\% - 14\%)/(63\% - 14\%)$).

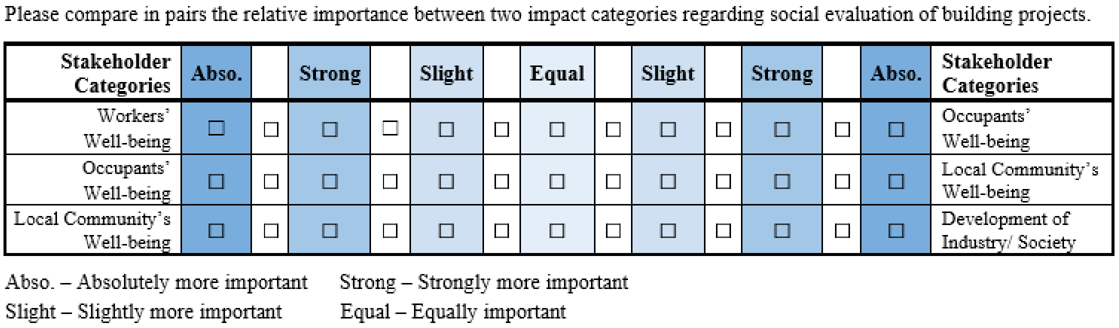
Another example is evaluating worker's health and safety using accident frequency rate (AFR, calculated by 1,000,000 times the ratio of the number of workplace accidents to the number of man-hours worked). country-level statistics is selected as PRV, which is 1.50 in Singapore (MOM, 2016). Score of +2 is assigned if no injure occurs, indicating best performance; score of -1 is assigned if AFR is identical to statistical (average) value, i.e., 1.5. Other values are normalized within the range of -2 to 0 based on PRVs, e.g., for a project with 2 minor injure cases and 164,500 man-days (averagely, 9.5 hours per man-day) recorded, its AFR is calculated as 1.28; accordingly, performance score is -0.85 ($= -1 * 1.28/1.50$).

3.3. Weights

Weights among social impact subcategories were obtained through questionnaire survey. The main part of the questionnaire was designed in a pairwise comparison manner, which was based on AHP method using consistent fuzzy preference relations (CFPR). Linguistic terms are used to describe the relevant importance and are converted into corresponding numbers for further calculation. CFPR-based AHP can be seen as the deviation of the traditional AHP process. Traditional AHP process involves $n(n-1)/2$ pairs of comparison in a group of n

criteria, which brings some issues when there are too many criteria involved. Faced with a quite long questionnaire, experts usually do not have enough time or patience to complete it. Furthermore, too many pairs of comparison may cause experts' mental confusion, resulting in inconsistent responses, in which case, the questionnaire needs to be checked and re-answered, leading to inefficiency (Chen and Chao, 2012). However, in CFPR-based AHP, ith criterion is only compared with $(i+1)$th criterion, which means only $(n-1)$ judgments are involved, and consistency can also be guaranteed. For detailed methodology of CFPR-based AHP, please refer to previous studies, such as (Herrera-Viedma et al., 2004) and (Wang et al., 2016).

Questionnaires, including respondents' basic information, main pairwise comparison part and corresponding explanations, were delivered via face-to-face distribution or e-mail to local construction experts. Fig. 5 present an example of the main pairwise comparison part of the questionnaire. In total 67 feedbacks were received with a response rate of 72.3%. The respondents covered various stakeholders as shown in Fig.6. The collected responses were dealt with via CFPR-based AHP process, as explained in detail in Supplementary Document (S2), and weights were derived as showed in Table 3.



Please compare in pairs the relative importance between two impact categories regarding social evaluation of building projects.

Stakeholder Categories	Abso.		Strong		Slight		Equal		Slight		Strong		Abso.	Stakeholder Categories
Workers' Well-being	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Occupants' Well-being
Occupants' Well-being	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local Community's Well-being
Local Community's Well-being	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Development of Industry/ Society

Abso. – Absolutely more important
Strong – Strongly more important
Slight – Slightly more important
Equal – Equally important

Fig.5 Part of the pairwise comparison part of the questionnaire in this study

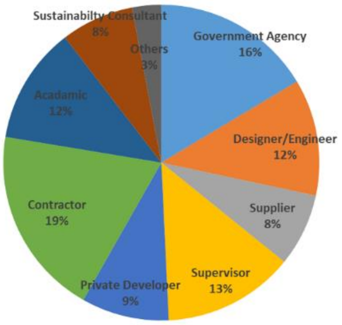


Fig.6 Distribution of responses of questionnaire survey

Table 3 Weights of Social Impact Categories

Stakeholder Category	Subcategory	Local weights	Global weights
Worker		***0.273***	
	Health and Safety	0.254	0.069
	Fair Salary	0.233	0.064
	Working Hours	0.186	0.051
	Discrimination	0.175	0.048
	Forced Labour	0.085	0.023
	Child Labour	0.067	0.018
Occupant		***0.283***	
	Functionality and Usability	0.312	0.088
	Health and Comfort	0.307	0.087
	Accessibility	0.209	0.059
	Feedback Mechanism	0.172	0.049
Local Community		***0.243***	
	Safety and Health	0.343	0.083
	Accessibility	0.191	0.046
	Integration and Interaction	0.170	0.041
	Local Employment	0.296	0.072
Society		***0.201***	
	Technology development	0.621	0.125
	Public Commitment to Sustainability Issues	0.379	0.076

Another set of weights are weights among life cycle phases. Previous studies usually use activity variables to "reflect the share of a given activity associated with each unit process" and to describe the relevance of impacts caused by a process in a life cycle. Currently, the most common activity variable is worker hours, i.e. the time workers spend to produce certain amount of products in the given process or sector. However, strictly speaking, worker hours are only related to the stakeholder workers (Ciroth and Eisfeldt, 2017), which is very relevant in previous studies that only discuss topics regarding labor conditions. In this study, worker hours, however, may not be a suitable activity variable as it includes multiple stakeholders.

This study indicatively estimated the relative importance of each phase based on two considerations, as shown in Table 4. One is the degree of possibility to place control. As indicated in Fig.3, data specificity is lower if the activities are located farther from the center phases; so is the control possibility. Therefore, the possibility to control is ranked from high to low as follows: construction phase, use phase, production phase, and raw material extraction phase. Use phase is weaker than construction phase due to its longer time span (around 50 years). Another aspect is level of concern of construction practitioners, whose focus is on construction and use phase; raw material extraction was given a relatively higher score, since mining industry is believed to have much severer negative social impact compared with manufacturing industry. A total score of 100 was allocated to four phases for each aspect of consideration, and for each phase mean of two scores was calculated and converted to weight.

Table 4 Weights of life cycle phases

	Raw Material Extraction	Production	Construction	Use
Control	5	15	50	30
Concern	25	5	30	40
Weight	0.15	0.10	0.40	0.35

4. Case study

This section presents a case study comparing life-cycle social performance of two buildings adopting different construction methods. One is a student residential hall project located in Singapore whose total gross floor area is 48,550 m^2. It adopts prefabricated prefinished volumetric construction (PPVC) method, which is promoted locally in Singapore to enhance productivity in building industry that is traditionally manpower-intensive. It adopts free-standing volumetric modules (complete with finishes for walls, floors and ceilings) that are manufactured and assembled in an accredited fabrication facility and then installed on site. In this project, PPVC is principally a steel-type module and is adopted for the typical units of the building with its modular design and standardized dimensions, accounting for around 45% of the total gross floor area. Conventional cast-in-situ construction is adopted for podium levels, transfer slab and core areas. For this project, material quantity data was obtained through actual design documents, Bill of Quantities, and other relevant reports.

Another project is a general residential project that were published as a case study in a previous study (Mao et al., 2013). It is a semi-prefabricated reinforced concrete structure building with 10% of the total concrete volume being prefabricated, including precast facades, staircases and corridor slab. For this project, material quantity data was derived from Mao et al. (2013). To facilitate further comparison, a consistent calculation basis should be established. Therefore, the size of this semi-prefabrication project, which is 216, 000 m^2, was adjusted to 48,550 m^2, being identical to the PPVC project. Accordingly, the material usage was adjusted proportionally.

In this case study, the main focus is to compare two projects adopting different construction methods and different structural frames. Thus, only structure related parts were considered while common parts such as windows and paintings were excluded from further analysis. In addition, it was assumed that these two projects are completed by the same contractor, which means the difference regarding managerial practices in the site-specific analysis should be caused by different features of different construction methods, rather than by different management skills of different contractors. Similarly, it was also assumed that these two projects are located in the same place in Singapore, which means the neighbourhood characters will not influence the final assessment results. Basic information and main materials usage of these two projects are summarized in Table 5.

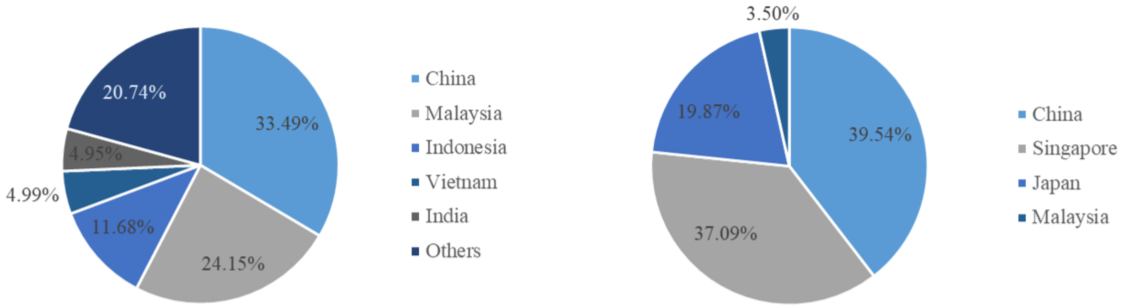
Table 5 Summary of basic information and material usage for two designs (unit: ton)

	PPVC project		Semi-Prefabrication project	
Basic Information				
Structural frame	Steel Structure		Concrete Structure	
Construction Method	45% of total gross floor area being PPVC modules + Conventional cast-in-situ concrete		10% of the total concrete volume being prefabricated concrete components + Conventional cast-in-situ concrete	
Materials	Off-Site	On-Site	Off-Site	On-Site
Concrete	-	37,135	6,289	53,749
Brick	-	2,089	-	11,844
Mortar	-	362	-	2,937
Steel reinforcing bars	-	1,986	409	2,558
Steel structural members	3,470	-	-	-
Promat boards* (fireproofing)	2,420	-	-	-

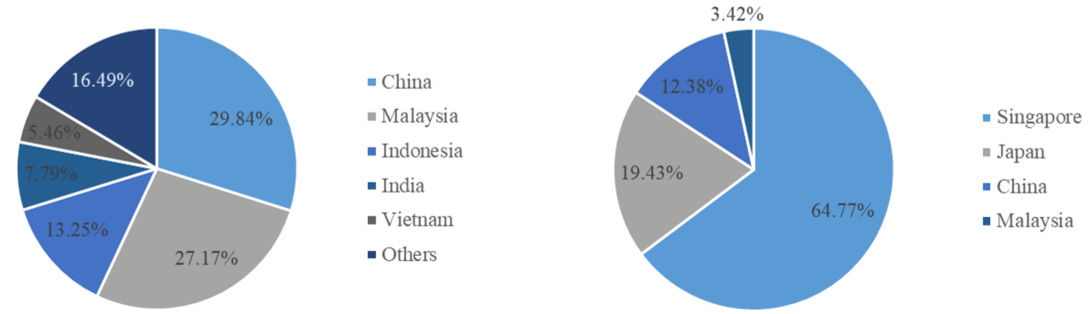
* Promat boards are lightweight, non-combustible, fire resisting calcium silicate boards for walls, ceilings and floors, which are installed in PPVC modules mainly for fireproofing purpose of steel structure.

4.1. Generic Analysis

Generic analysis was conducted on raw material extraction as well as manufacturing and fabrication phase. Activity contributions of countries involved in these two phases of two designs are shown in Fig.7 and were obtained based on material quantity information and material extraction or import statistical data. As observed from Fig.7a and Fig.7b, most of the activities were carried out in China, Malaysia and Indonesia for both designs in raw material extraction, which was mainly due to their provisions of crude steel, crushed stone and sand. For manufacturing and fabrication phase (see Fig.7c and Fig.7d), since PPVC modules were produced in China, while prefabricated concrete components were fabricated in Singapore, main activity contributors of two designs are different.



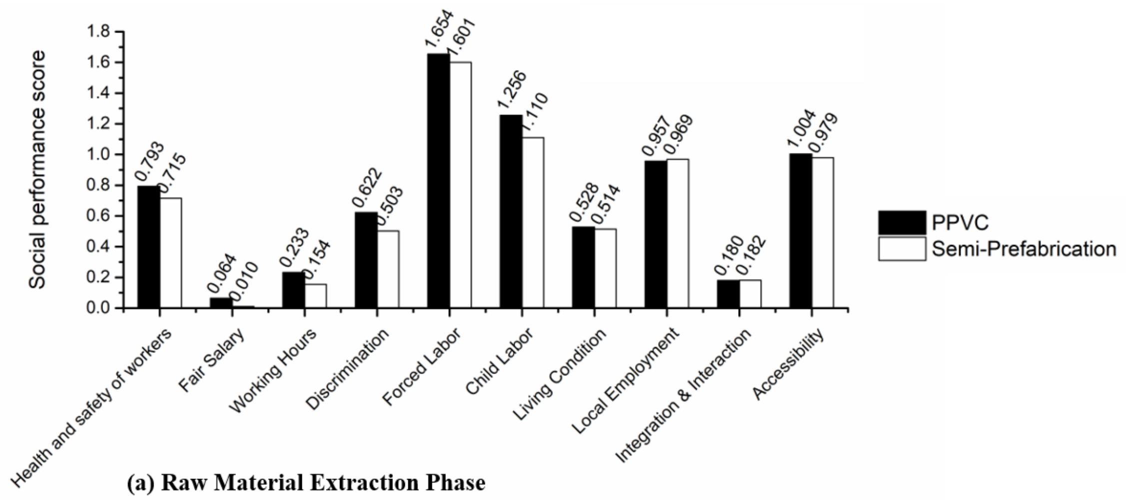
(a) Raw Material Extraction_PPVC (c) Manufacturing & Fabrication_PPVC



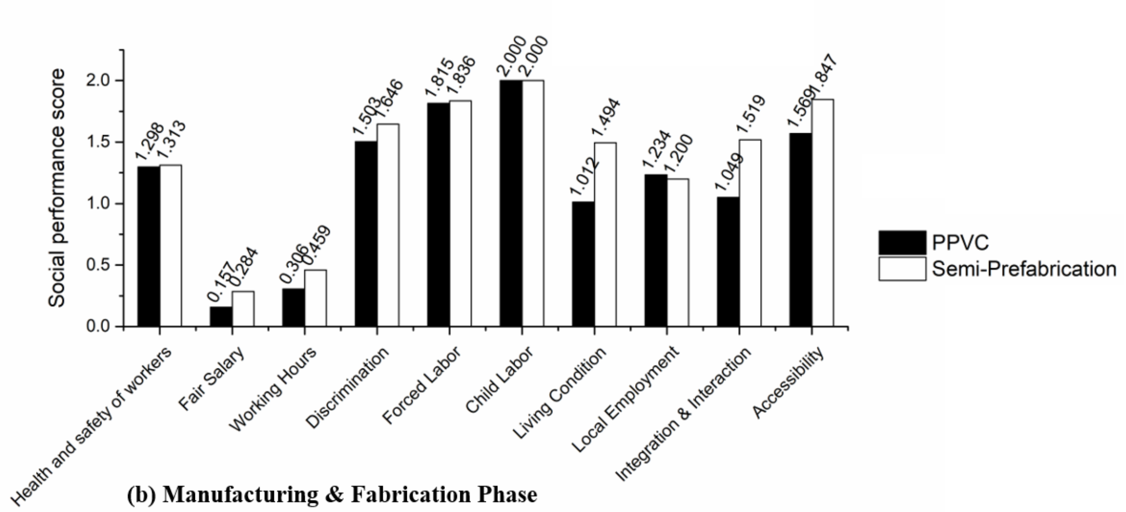
(b) Raw Material Extraction_Semi-Prefab. (d) Manufacturing & Fabrication_Semi-Prefab.

Fig.7 Activity contribution of countries involved in raw material extraction, manufacturing and fabrication processes

Social performance scores, illustrated in Fig.8, were then obtained using information on activity contribution of countries, together with country-level social performance score for different impact subcategories. For raw material extraction phase, PPVC project performs better in most indicators, but the differences are not significant for most indicators. For manufacturing and fabrication phase, semi-prefabrication project performed much better due to the higher activity contribution of Singapore, which performed much better in most of the indicators except for *local employment*.



(a) Raw Material Extraction Phase



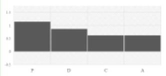
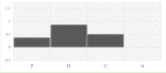
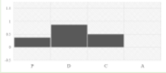
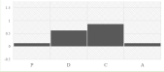
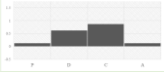
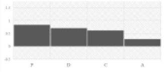
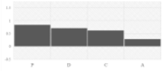
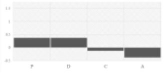
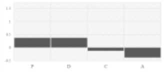
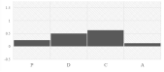
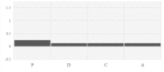
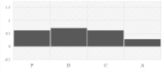
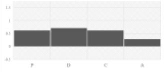
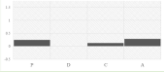
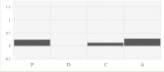
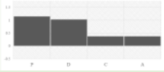
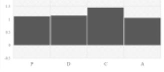
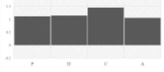
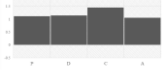
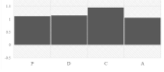
(b) Manufacturing & Fabrication Phase

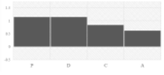
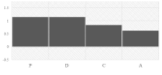
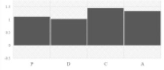
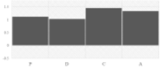
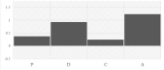
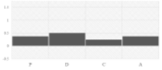
Fig.8 Comparison of social performance score of PPVC and semi-prefabrication buildings in raw material extraction, and manufacturing and fabrication phase

4.2. Site-Specific Analysis

Site-specific analysis was conducted to investigate social performance in construction and use phase. Information regarding managerial practices were collected through people from project management team, including assistant project director, project managers (from both developer and contractor), safety supervisors, site engineer, lifting supervisors, construction manager, and WSH officers. As for design consideration, interview with designers and project managers was conducted. Sources for information on direct social performance includes project records or design parameters for quantitative indicators, as well as on-site observation and interviewed with relevant stakeholders, such as neighbourhood, pedestrians/bicyclists passing by and students living in, for semi-quantitative indicators. Collected data were calculated and normalized, and further integrated via averaging of two aspects (managerial practices/design consideration and direct social performance). The results for managerial practices or design consideration, and direct social performance are presented in Table 6, and integrated score is presented in Fig.9.

Table 6 social performance scores of PPVC and semi-prefabrication building in construction and use phase

Impact Category		Managerial practices/ design consideration				Direct social performance	
		PPVC		Semi-Pref.		PPVC	Semi-Pref.
Worker (Construction)	Worker's Health and Safety		*0.988		0.819	**2.000**	-0.125
	Fair Salary		0.438		0.438	0.600	0.600
	Working Hours		0.438		0.438	0.920	0.920
	Discrimination		0.188		0.188	2.000	2.000
	Forced Labor **	-	0.000	-	0.000	2.000	2.000
	Child Labor **	-	0.000	-	0.000	2.000	2.000
Local Community (construction)	Living Condition		0.617		0.617	**1.550**	1.480
	Local Employment		0.063		0.063	0.200	**0.260**
	Integration and Interaction		0.376		0.156	0.970	0.970
	Accessibility		0.563		0.563	1.188	**1.200**
Local Community (Use)	Living Condition		0.136		0.136	0.321	0.321
	Local Employment		0.189		0.189	1.640	1.640
	Integration and Interaction		0.166		0.166	0.127	0.127
	Accessibility		0.731		0.731	1.570	1.570
Occupant (Use)	Functionality and Usability		1.196		1.196	1.730	1.730
	Health and Comfort		1.196		1.196	0.760	**1.032**

	Accessibility		0.942		0.942	1.680	1.680
	Feedback Mechanism		1.233		1.233	1.780	1.780
Society	Technology development		0.700		0.375	**1.500**	0.500
	Public commitments to sustainability issues		0.031		0.031	0.500	0.500

* From left to right are P, D, C, A, respectively, in bar charts

** For *forced labor* and *child labor*, no information regarding managerial practices were available and actual performance is assumed to be identical to country-level performance, i.e., Singapore average performance

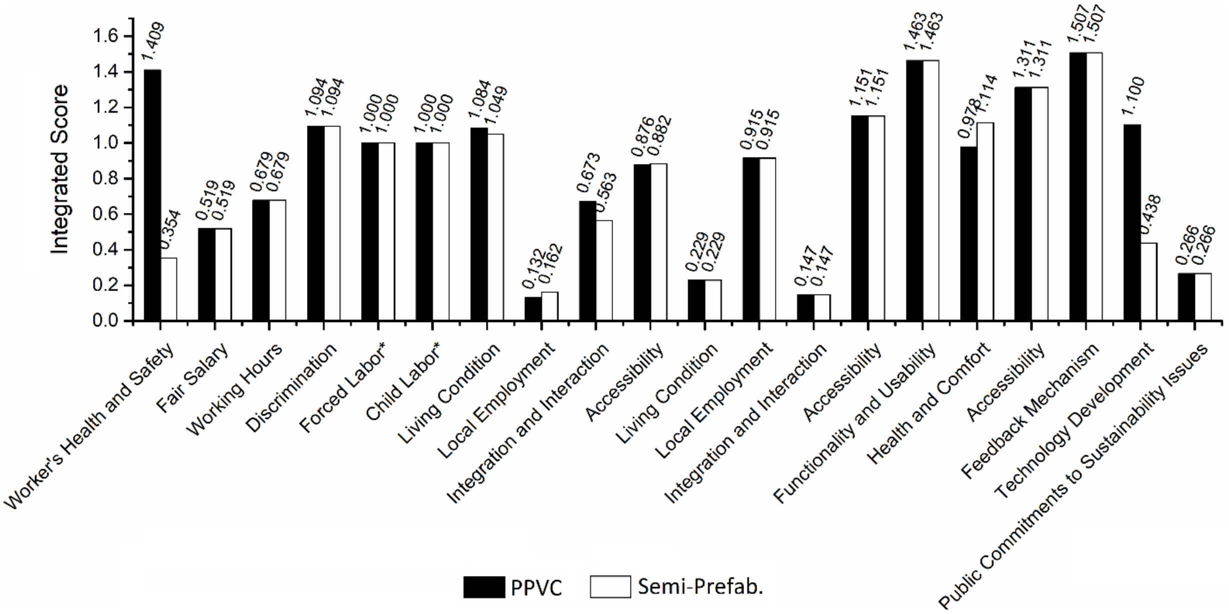


Fig.9 Integrated social performance scores of PPVC and semi-prefabrication building in construction and use phase

In Table 6, for managerial practices/ design consideration, four aspects of PDCA cycle are shown in a column chart, and the average of the four aspects was calculated. Specifically, PPVC project performs better in *worker's health and safety* since it involves less people working at height for construction; it also performs better in *integration and interaction*, and *technology development*, since project teams organized regular meeting open to the public and shared their experience regarding modular construction, which created chances to communicate with and get feedback from local community, and thus performed proactively regarding technology development. Otherwise, two projects gain the same score for most other impact categories due to involvement of the same contractor and developer.

For direct social performance, PPVC project performed better in *worker's health and safety* since there was no injure recorded and in *local community's living conditions* as the construction period was quiet and with less construction noise. Performance of PPVC in *Integration and integration* and *technology development* are also better due to regular sharing sessions as previously mentioned. Semi-prefabrication project performs better in local employment because of larger share of purchasing from local supplier; yet, it is worth mentioning that local workforce percentage of PPVC project is higher than that of semi-prefabrication project, which are 20% and 17% respectively. *Accessibility of local community* during construction period of PPVC project also gained less score due to some complaints that there are always trucks that carry a PPVC module waiting outside the construction site, and thus influence the mobility of pedestrians and drivers. Furthermore, PPVC projects, being a steel-structure building, performed worse regarding thermal and acoustic comfort. Almost all the occupants interviewed complained about sound-proof issue.

4.3. Integrated Social Sustainability Performance

Based on the performance scores and weight sets as provided in section 3.3, single social performance scores were calculated as 0.926 and 0.821 for PPVC and semi-prefabrication project, respectively. This indicates an overall better social performance of PPVC project from life-cycle perspective. Detailed comparison results were summarized in Figs. 10 and 11.

As indicated in Fig. 10, PPVC performs significantly better in *worker's health and safety* and *technology development* due to the shortened working time at height and active actions in adopting new construction technology and technology sharing. Significant advantage in these two aspects also explained the better performance regarding stakeholder *worker* and *society* of PPVC project, as illustrated in Fig.11. PPVC, when adopting a steel-structure skeleton, does not perform as well as semi-prefabricated concrete-structure building in *occupant's health and comfort* due to relatively poor thermal and sound comfort. As for *local employment*, PPVC does not show much advantage from life-cycle perspective although resident workforce percentage of PPVC project is slightly increased, as PPVC modules are manufactured in China and thus lower the share of purchasing from local suppliers in this project.

Fig.10 Scores of social impact subcategories for PPVC and semi-prefabrication projects

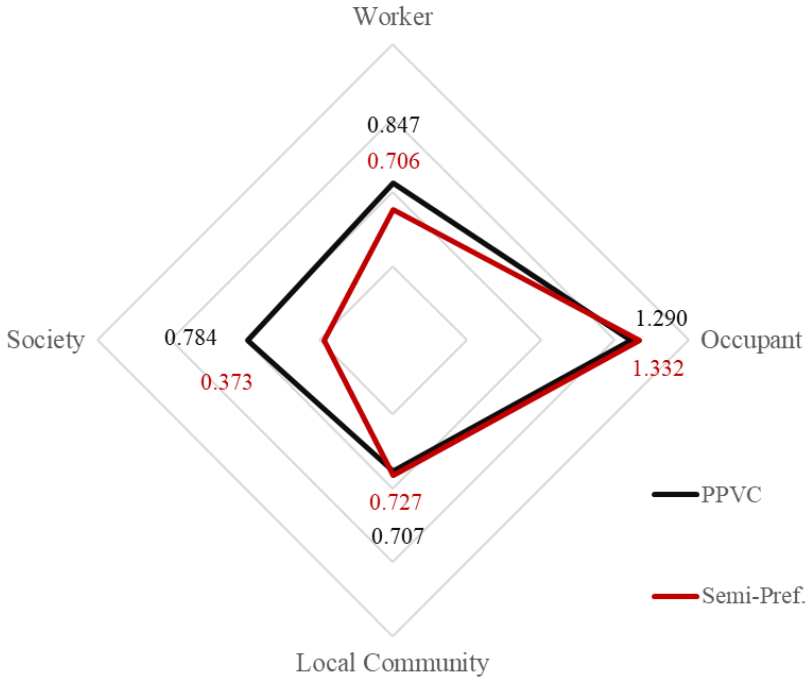
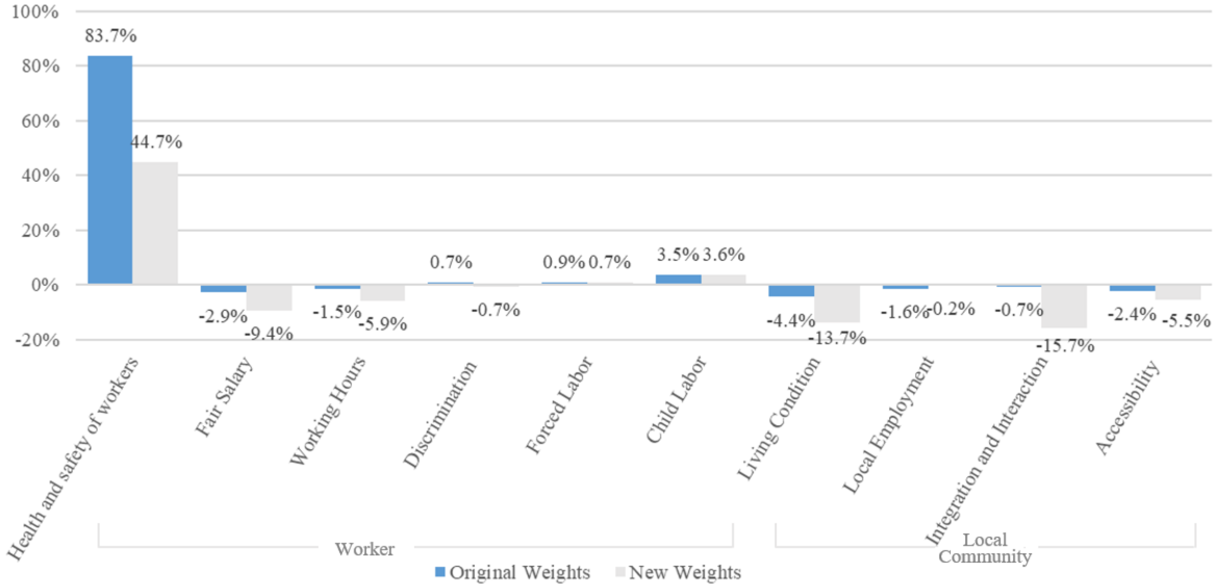


Fig.11 Scores of stakeholder categories for PPVC and semi-prefabrication projects

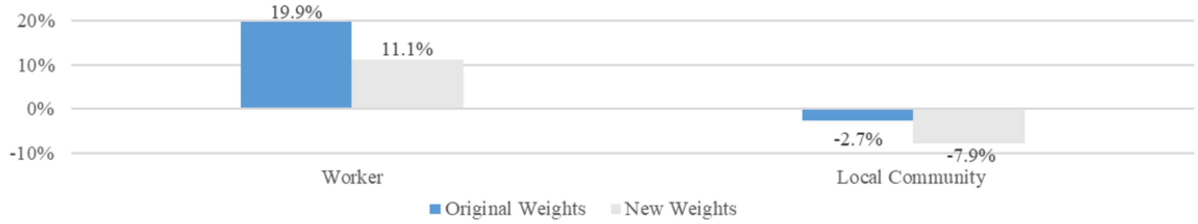
4.4. Sensitivity Analysis

Sensitivity analysis can help with interpretation of results in the case study. One of the main uncertainty sources in this study is the weight sets, especially weights among different phases, as provided in Table 4. This analysis adopted another set of phase weights in a previous building-related study (Hosseinijou et al., 2014), in which weights were obtained from experts' opinions through AHP process. The new phase weight set was extracted as 0.26, 0.26, 0.24, 0.24 for the four phases. Compared with original weights set, it weighs life-cycle phases almost equally and puts slightly more emphasis on the raw material extraction and manufacturing phases.

Change on phase weights influenced the comparison results of stakeholder *worker* and *local community*. As illustrated in Fig.12, advantage of the PPVC project become much less when compared with the semi-prefabrication project in worker category, and the performance of the PPVC project in local community category become much worse. This is because that the semi-fabrication project performed better in manufacturing phase (as shown in Fig.8b), *while* the PPVC project showed more advantage in the construction phase (as shown in Fig.9). However, as for overall performance, the PPVC project still gained a higher score of 0.944 than that of the semi-fabrication project, 0.868.



(a) relative change in impact subcategories



(b) relative change in stakeholder categories

Fig.12 Relative change of the score of PPVC project to semi-prefabrication project

Note: The value was calculated by (score of PPVC project - score of semi-prefabrication project)/ score of semi-prefabrication project; positive values show that PPVC project performs better, and vice versa.

5. Conclusion and future work

This study proposed a methodological framework for social sustainability assessment of buildings. It applies multi-stakeholder approach and includes several life-cycle phases in the analysis which enables the investigation on potential transfer of impacts between life-cycle phases.

Firstly, a theoretical framework for social sustainability assessment was constructed through the identification of relevant stakeholders (in this study, worker, occupant, local community and society) and impact subcategories associated with each stakeholder category. Secondly, weights among these impact subcategories were generated through questionnaire survey which is designed based on CFPR-based AHP method. Furthermore, weights among life-cycle phases were determined considering the degree of possibility to place control as well as level of concern of construction practitioners. Thirdly, indicators were selected for each impact subcategory based on the assessment objective and data availability. Indicators were categorized into three groups by data source and indicator type, including quantitative indicators in generic analysis, as well as quantitative and semi-quantitative indicators in site-specific analysis.

Indicator selection was followed by proposed scoring method for each type of indicators. For generic analysis, SPS were obtained by integrating country activity contribution and normalized country-level performance scores, which were calculated from different sources of statistics. For site-specific analysis, SPS were the average of scores for organizational managerial practices and direct social performance. Organizational managerial practices adopted semi-quantitative indicators and their scores were obtained based on performance reference scales (PRS). The PRS scales are constructed based on PDCA Cycle theory, aided by fuzzy theory for the conversion of qualitative evaluation results. As for direct social performance, score for semi-quantitative indicators were also obtained using PRSs and fuzzy numbers. Score for quantitative indicators were calculated using actual performance data and performance reference values (PRVs), which can be country and/or sector average performance values.

The proposed method was then applied to a case study comparing two buildings with different structural frames, namely PPVC project and semi-prefabrication project. Single SPSs of two projects indicated that PPVC outperformed semi-prefabrication in terms of social sustainability. It is mainly caused by its better performance in *worker's health and safety* and *technology development* due to shortened working time at height and active actions in adopting new construction technology and technology sharing. Nevertheless, PPVC, when adopting a steel-structure frame, did not perform as well as semi-prefabrication concrete structure one regarding *occupant's health and comfort* due to relatively poor thermal and sound comfort. This however may be improved if different material is adopted in PPVC, e.g. lightweight concrete. Furthermore, PPVC did not show much advantage from the life-cycle perspective in *local employment* as PPVC modules are manufactured in foreign country and thus lower the share of purchasing from local suppliers. This consideration however should be balanced by the cost effectiveness of the overall project, which is out of the scope of this study.

This study has several practical implications to practitioners in the construction industry. Firstly, social sustainability performance can be an integral element of both corporate-level and project-level strategies, and should be assessed and optimized during the planning and design of a construction project development. In addition, in order to achieve social sustainability throughout the entire supply chain, project team is supposed to act as a whole to consider life-cycle performance of a project rather than conducting evaluation separately by different parties (i.e., designer, owner and contractor). Furthermore, the adoption of so-called sustainable techniques or designs cannot guarantee the success of social sustainability. In other words, there is no such single best solution towards sustainability. Social sustainability is highly associated with the country activity contribution, and thus locations of various activities along the entire supply chain should be considered and carefully planned.

Implication for policy is that the government should take measures to promote the emphasis on social sustainability in the construction industry. For one thing, the government should make efforts to provide data support for the social assessment. As discussed previously, data availability for social assessment restricts the selection of indicators and study scope. Reliable and sustain data are the foundations for a reliable assessment model (Ma and Cai, 2018; Ma et al., 2018). Therefore, official statistical yearbook should be issued by the government at both national and sectorial levels. For another, more aspects regarding social sustainability covering different stakeholders should be included in the sustainability assessment scheme, such as the

BCA GreenMark Scheme of Singapore. This will encourage the industry to pay attention to the potential risk of socially unsustainable actions and will go a long way toward changes in industry mind-set about sustainable construction/ building practices.

Implications for the research community are to conduct further research on developing decision support tools to integrate social sustainability considerations in the selection of construction methods such that the conceptual social sustainability requirements can be transferred to the industrial practices. As the base of such decision support tool, the proposed social sustainability assessment method still require further attention regarding some methodological issues. Indicators selected to characterize impact categories need continuous improvement through investigation of cause-effect relationships. Furthermore, the analysis scope could be broadened to include maintenance and end-of-life phases, which were excluded in this study due to data unavailability. In addition, generation of weights for different phases, or activity variables, is still ambiguous yet very critical since they will influence the evaluation results greatly as illustrated in the sensitivity analysis. This study estimated weights from two aspects of consideration, however it deserves further investigation and extensive survey; alternatively, other activity variables besides worker hour need to be proposed and tested when multiple stakeholders are involved.

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